

Semi-empirical bound on the ^{37}Cl solar neutrino experiment

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ABSTRACT

The Kamiokande measurement of energetic ^8B neutrinos from the sun is used to set a lower bound on the contribution of the same neutrinos to the signal in the ^{37}Cl experiment. Implications for ^7Be neutrinos are discussed.

Energetic ^8B neutrinos from the sun have been detected in the Kamiokande experiment [1] at about one half the rate predicted by the Standard Solar Model (SSM) [2]. These same neutrinos must also interact with the ^{37}Cl detector [3] and so it is important to understand their contribution to the measured ^{37}Cl signal. By comparing this contribution to the total signal, we can extract information about other parts of the solar neutrino spectrum, especially ^7Be .

We find that, even allowing for neutrino flavor oscillations, the Kamiokande experiment imposes a bound on the ^{37}Cl signal that does not leave much room for a significant contribution from ^7Be neutrinos. This finding is not inconsistent with the latest results from the ^{71}Ga experiments [4,5], and so we may refine the statement of the solar neutrino problem to read: Where have all the ^7Be neutrinos gone?

Since the basic physical process in the Kamiokande and ^{37}Cl experiments are different, the former being neutrino-electron scattering and the latter neutrino capture on ^{37}Cl , we must follow a semi-empirical method to relate them to one another. In Kamiokande, the calculated signal involves a convolution over $\phi(E_\nu)$, the SSM spectrum of ^8B neutrinos with energy E_ν , the differential cross section for scattered electrons with kinetic energy T , and the electron resolution function $\theta(T, T')$ which represents the probability that T will appear as T' in an actual measurement. We

call this function $\phi\sigma(\nu_e e; E_\nu)$ and plot in Fig. 1 its normalized shapes as a function of E_ν for two choices of $\theta(T, T')$: The first is a Gaussian shape that closely approximates the actual experimental resolution [6], the second is a δ -function representing perfect resolution, and both assume $7.5 \leq T' \leq 15$ MeV. Notice that because of the experimental resolution, the first case has developed a significant tail below the 7.5 MeV threshold. Only the first case with the experimental resolution will be used for calculations below.

In the ^{37}Cl experiment, the relevant quantity is the product of $\phi(E_\nu)$ with the total capture cross section [7] for neutrinos of energy E_ν on ^{37}Cl . We call this function $\phi\sigma(^{37}\text{Cl}; E_\nu)$ and plot its normalized shape also in Fig. 1. The integral of $\phi\sigma(^{37}\text{Cl}; E_\nu)$ gives the ^8B contribution to the SSM signal in ^{37}Cl , $R_{\text{SSM}}(^7\text{Be}; ^{37}\text{Cl})$.

Comparing the normalized functions for the two experiments, we see that they are remarkably similar to one another, especially at the high energy end. We therefore write

$$\frac{\phi\sigma(^{37}\text{Cl}; E_\nu)}{\int \phi\sigma(^{37}\text{Cl}; E_\nu) dE_\nu} = \alpha \frac{\phi\sigma(\nu_e e; E_\nu)}{\int \phi\sigma(\nu_e e; E_\nu) dE_\nu} + r(E_\nu) , \quad (1)$$

where α is a constant whose value is maximized subject to the condition that the remainder function $r(E_\nu)$ be everywhere positive. It turns out that the largest value of α is 0.93, and so we obtain an inequality

$$\phi\sigma(^{37}\text{Cl}; E_\nu) \geq 0.93 \frac{R_{\text{SSM}}(^8\text{B}; ^{37}\text{Cl})}{R_{\text{SSM}}(\text{Kam})} \phi\sigma(\nu_e e; E_\nu) . \quad (2)$$

The next step of the argument is to note that the actual quantity measured in these experiments involves the product of $\phi\sigma$ with an electron-neutrino “survival probability” $P(E_\nu)$ which, in general, may be a function of the neutrino energy E_ν . If $P(E_\nu)$ represents some, possibly energy-dependent, reduction of the ^8B spectrum, or an oscillation into a sterile neutrino, then we find from Eq. (2) that

$$\int \phi\sigma(^{37}\text{Cl}; E_\nu) P(E_\nu) dE_\nu \geq 0.93 \frac{\int \phi\sigma(\nu_e e; E_\nu) P(E_\nu) dE_\nu}{R_{\text{SSM}}(\text{Kam})} R_{\text{SSM}}(^8\text{B}; ^{37}\text{Cl})$$

or

$$\begin{aligned} R(^8\text{B}; ^{37}\text{Cl}) &\geq 0.93 (0.50 \pm 0.08) (6.1 \text{ SNU}) \\ &= (2.84 \pm 0.45) \text{ SNU} , \end{aligned} \quad (3)$$

where we have used the most recent result from the Kamiokande experiment [1]. This falls within the errors of the twenty-year average of the Davis value [3]

$$\langle R_{\text{Davis}} \rangle = 2.32 \pm 0.23 \text{ SNU} , \quad (4)$$

but is somewhat on the high side. Note that the bound in Eq. (3) also holds in the simple case of a reduction of the total ^8B flux with no change in the spectral shape.

Next, consider the case of oscillations of solar electron-neutrinos into ν_μ or ν_τ , or some combination thereof. The signal observed in Kamiokande is then given by

$$R(\text{Kam}) = \int \left(\phi\sigma(\nu_e e; E_\nu) P(E_\nu) + [1 - P(E_\nu)] \phi\sigma(\nu_\mu e; E_\nu) \right) dE_\nu , \quad (5)$$

where we must now distinguish between the cross sections for electron-neutrinos and muon- or tau-neutrinos. As is well known [7] the latter cross section lies somewhere between 1/6 and 1/7 of the former in magnitude and is very similar in shape for energetic neutrinos. For our case it is an extremely good approximation to set

$$\sigma(\nu_\mu e; E_\nu) = 0.148 \sigma(\nu_e e; E_\nu) . \quad (6)$$

We can then rewrite Eq. (5) in the form

$$\int \phi \left(\sigma(\nu_e e; E_\nu) - \sigma(\nu_\mu e; E_\nu) \right) P(E_\nu) dE_\nu = R(\text{Kam}) - \int \phi \sigma(\nu_\mu e; E_\nu) dE_\nu ,$$

or

$$0.852 \int \phi \sigma(\nu_e e; E_\nu) P(E_\nu) dE_\nu = R(\text{Kam}) - 0.148 R_{\text{SSM}}(\text{Kam}) . \quad (7)$$

From Eqs. (2) and (7) and the Kamiokande data [1], we see that the contribution of the ^8B neutrinos must be bounded in the case of flavor oscillations by

$$\begin{aligned} R(^8\text{B}; ^{37}\text{Cl}) &= \int \phi \sigma(^{37}\text{Cl}; E_\nu) P(E_\nu) dE_\nu \\ &\geq 0.93 \frac{\int \phi \sigma(\nu_e e; E_\nu) P(E_\nu) dE_\nu}{R_{\text{SSM}}(\text{Kam})} R_{\text{SSM}}(^8\text{B}; ^{37}\text{Cl}) \\ &= 0.93 \frac{(0.50 \pm 0.08) - 0.148}{0.852} (6.1 \text{ SNU}) \\ &= (2.34 \pm 0.53) \text{ SNU} . \end{aligned} \quad (8)$$

To show that the above argument really does provide lower bounds on the ^7Be neutrino contribution to the ^{37}Cl experiment, we consider the special case in which, inspired by the non-adiabatic MSW solution [8], we take the electron-neutrino survival probability to be [9]

$$P(E_\nu) = e^{-C/E_\nu} , \quad (9)$$

where C is a constant to be determined by fitting the Kamiokande data. When there is either no oscillation, or oscillation into a sterile neutrino, we find

$$C = 6.9_{-1.5}^{+1.8} \text{ MeV} \quad \text{and} \quad R(^8\text{B}, ^{37}\text{Cl}) = 3.0 \pm 0.5 \text{ SNU} . \quad (10)$$

Allowing for neutrino oscillations, we find instead

$$C = 8.8_{-2.0}^{+2.6} \text{ MeV} \quad \text{and} \quad R(^8\text{B}, ^{37}\text{Cl}) = 2.5 \pm 0.5 \text{ SNU} . \quad (11)$$

Both rates are larger than the corresponding lower bounds in Eqs. (3) and (8) respectively.

When compared with the Davis result of Eq. (4), our bounds on the energetic ^8B neutrino contribution in Eq. (3) and (8) do not leave much room for the 1.8 SNU coming from all other sources, or the 1.1 SNU from ^7Be neutrinos alone. Indeed, the contribution from all other sources, call them X , is given in the two cases we have considered by

$$R(X, ^{37}\text{Cl}) \leq \begin{cases} -0.52 \pm 0.51 \text{ SNU} & (\text{no oscillations}), \\ -0.02 \pm 0.58 \text{ SNU} & (\text{with oscillations}). \end{cases} \quad (12)$$

At the 95% confidence limit, this means

$$R(X, ^{37}\text{Cl}) \leq \begin{cases} 0.32 \text{ SNU} & (\text{no oscillations}), \\ 0.93 \text{ SNU} & (\text{with oscillations}). \end{cases} \quad (13)$$

Assuming that the ^7Be contribution is approximately 1.1/1.8, or 60% of this, we find it to be:

$$R(^7\text{Be}, ^{37}\text{Cl}) < \begin{cases} 0.20 \text{ SNU} & (\text{no oscillations}), \\ 0.57 \text{ SNU} & (\text{with oscillations}). \end{cases} \quad (14)$$

To pursue this line of argument further, we can set lower bounds on the contribution of the ^8B neutrinos to the ^{71}Ga experiments. Replacing the absorption cross section of ^{37}Cl by that of ^{71}Ga everywhere [10], we obtain an inequality similar to Eq. (2) but with $\alpha = 0.81$. The bounds on the ^8B contribution to the ^{71}Ga experiments are

$$R(^8\text{B}, ^{71}\text{Ga}) \geq \begin{cases} 5.7 \pm 0.9 \text{ SNU}, & (\text{no oscillations}), \\ 4.7 \pm 1.1 \text{ SNU}, & (\text{with oscillations}). \end{cases} \quad (15)$$

The corresponding values in the $e^{-C/E}$ model,

$$R(^8\text{B}, ^{71}\text{Ga}) = \begin{cases} 6.6 \pm 1.1 \text{ SNU}, & (\text{no oscillations}), \\ 5.5 \pm 1.3 \text{ SNU}, & (\text{with oscillations}), \end{cases} \quad (16)$$

are again larger than their counterparts in Eq. (15).

Combining the bounds of Eq. (15) with the latest ^{71}Ga results [4,5],

$$\begin{aligned} R(^{71}\text{Ga}) &= \begin{cases} 79 \pm 12 \text{ SNU}, & \text{GALLEX} \\ 73 \pm 19 \text{ SNU}, & \text{SAGE} \end{cases} \\ &= 77 \pm 10 \text{ SNU}, \quad (\text{combined}) \end{aligned} \quad (17)$$

we find an interesting situation, namely that the sum of the signals from pp neutrinos, ^7Be neutrinos, and other non- ^8B sources is very close to the SSM prediction of 71 SNU for pp neutrinos alone:

$$R(^{71}\text{Ga}) - R(^8\text{B}, ^{71}\text{Ga}) \leq \begin{cases} 72 \pm 12 \text{ SNU}, & (\text{no oscillations}), \\ 73 \pm 12 \text{ SNU}, & (\text{with oscillations}). \end{cases} \quad (18)$$

Scaling up the ^7Be neutrino bounds in Eq. (14) by the ratio of the capture cross sections on ^{71}Ga and ^{37}Cl , we find that the bounds on the ^7Be neutrino contribution to the ^{71}Ga signals are:

$$R(^7\text{Be}, ^{71}\text{Ga}) < \begin{cases} 6.0 \text{ SNU}, & (\text{no oscillations}), \\ 17.4 \text{ SNU}, & (\text{with oscillations}), \end{cases} \quad (19)$$

at the 95% confidence level. It will be interesting to test these bounds by direct observation of the ^7Be , or pp neutrinos themselves.

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Note added: After this work was completed, the authors learned from Prof. David Schramm that he had obtained a bound in the non-oscillation case similar to that in Eq. (3).

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Figure caption

Fig. 1. Normalized shapes of $\phi\sigma$ for various experiments.

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